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Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
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(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
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Lithographic apparatus, device manufacturing method, and device manufactured thereby

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Lithographic Apparatus, Device Manufacturing Method, and Device Manufactured Thereby

The present invention relates to a lithographic projection apparatus comprising:

– a radiation system for providing a projection beam of radiation;

– a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;

– a substrate table for holding a substrate;

– a projection system for projecting the patterned beam onto a target portion of the substrate;

– an aperture, through which the projection beam is directed;

– a detector ES for detecting a throughput of the projection beam through said aperture;

– means for directing the projection beam through said aperture.

The term "patterning means" as here employed should be broadly interpreted as referring to means that can be used to endow an incoming radiation beam with a patterned cross-section, corresponding to a pattern that is to be created in a target portion of the substrate; the term "light valve" can also be used in this context. Generally, the said pattern will correspond to a particular functional layer in a device being created in the target portion, such as an integrated circuit or other device (see below). Examples of such patterning means include:

- A mask. The concept of a mask is well known in lithography, and it includes mask types such as binary, alternating phase-shift, and attenuated phase-shift, as well as various hybrid mask types. Placement of such a mask in the radiation beam causes selective transmission (in the case of a transmissive mask) or reflection (in the case of a reflective mask) of the radiation impinging on the mask, according to the pattern on the mask. In the case of a mask, the support structure will generally be a mask table, which ensures that the mask

can be held at a desired position in the incoming radiation beam, and that it can be moved relative to the beam if so desired;

- A programmable mirror array. One example of such a device is a matrix-addressable surface having a viscoelastic control layer and a reflective surface. The basic principle behind such an apparatus is that (for example) addressed areas of the reflective surface reflect incident light as diffracted light, whereas unaddressed areas reflect incident light as undiffracted light. Using an appropriate filter, the said undiffracted light can be filtered out of the reflected beam, leaving only the diffracted light behind; in this manner, the beam becomes patterned according to the addressing pattern of the matrix-adressable surface. An alternative embodiment of a programmable mirror array employs a matrix arrangement of tiny mirrors, each of which can be individually tilted about an axis by applying a suitable localized electric field, or by employing piezoelectric actuation means. Once again, the mirrors are matrix-addressable, such that addressed mirrors will reflect an incoming radiation beam in a different direction to unaddressed mirrors; in this manner, the reflected beam is patterned according to the addressing pattern of the matrix-adressable mirrors. The required matrix addressing can be performed using suitable electronic means. In both of the situations described hereabove, the patterning means can comprise one or more programmable mirror arrays. More information on mirror arrays as here referred to can be gleaned, for example, from United States Patents US 5,296,891 and US 5,523,193, and PCT patent applications WO 98/38597 and WO 98/33096, which are incorporated herein by reference. In the case of a programmable mirror array, the said support structure may be embodied as a frame or table, for example, which may be fixed or movable as required; and

- A programmable LCD array. An example of such a construction is given in United States Patent US 5,229,872, which is incorporated herein by

reference. As above, the support structure in this case may be embodied as a frame or table, for example, which may be fixed or movable as required.

For purposes of simplicity, the rest of this text may, at certain locations, specifically direct itself to examples involving a mask and mask table; however, the general principles discussed in such instances should be seen in the broader context of the patterning means as hereabove set forth.

Lithographic projection apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In such a case, the patterning means may generate a circuit pattern corresponding to an individual layer of the IC, and this pattern can be imaged onto a target portion (e.g. comprising one or more dies) on a substrate (silicon wafer) that has been coated with a layer of radiation-sensitive material (resist). In general, a single wafer will contain a whole network of adjacent target portions that are successively irradiated via the projection system, one at a time. In current apparatus, employing patterning by a mask on a mask table, a distinction can be made between two different types of machine. In one type of lithographic projection apparatus, each target portion is irradiated by exposing the entire mask pattern onto the target portion in one go; such an apparatus is commonly referred to as a wafer stepper or step-and-repeat apparatus. In an alternative apparatus — commonly referred to as a step-and-scan apparatus — each target portion is irradiated by progressively scanning the mask pattern under the projection beam in a given reference direction (the "scanning" direction) while synchronously scanning the substrate table parallel or anti-parallel to this direction; since, in general, the projection system will have a magnification factor M (generally < 1), the speed V at which the substrate table is scanned will be a factor M times that at which the mask table is scanned. More information with regard to lithographic devices as here described can be gleaned, for example, from US 6,046,792, incorporated herein by reference.

In a manufacturing process using a lithographic projection apparatus, a pattern (e.g. in a mask) is imaged onto a substrate that is at least partially covered by a layer of radiation-sensitive material (resist). Prior to this imaging step, the substrate may undergo various procedures, such as priming, resist coating and a soft bake. After exposure, the substrate may be subjected to other procedures, such as a post-exposure bake (PEB), development, a hard bake and measurement/inspection of the imaged features. This array of procedures is used as a basis to pattern an individual layer of a device, e.g. an IC. Such a patterned layer may then undergo various processes such as etching, ion-implantation (doping), metallization, oxidation, chemo-mechanical polishing, etc., all intended to finish off an individual layer. If several layers are required, then the whole procedure, or a variant thereof, will have to be repeated for each new layer. Eventually, an array of devices will be present on the substrate (wafer). These devices are then separated from one another by a technique such as dicing or sawing, whence the individual devices can be mounted on a carrier, connected to pins, etc. Further information regarding such processes can be obtained, for example, from the book "Microchip Fabrication: A Practical Guide to Semiconductor Processing", Third Edition, by Peter van Zant, McGraw Hill Publishing Co., 1997, ISBN 0-07-067250-4, incorporated herein by reference.

For the sake of simplicity, the projection system may hereinafter be referred to as the "lens"; however, this term should be broadly interpreted as encompassing various types of projection system, including refractive optics, reflective optics, and catadioptric systems, for example. The radiation system may also include components operating according to any of these design types for directing, shaping or controlling the projection beam, and such components may also be referred to below, collectively or singularly, as a “lens”. Further, the lithographic apparatus may be of a type having two or more substrate tables (and/or two or more mask tables). In such “multiple stage” devices the

additional tables may be used in parallel, or preparatory steps may be carried out on one or more tables while one or more other tables are being used for exposures. Dual stage lithographic apparatus are described, for example, in US 5,969,441 and WO 98/40791, both incorporated herein by reference.

Developments in photolithographic techniques for improving image resolution have demonstrated the necessity of improving the quality of the radiation beam in the photolithographic system. Generally, such quality may be indicated by parameters as homogeneity of the beam, pointing of the beam, shape of the beam and divergence of the beam, further indicated as "beam quality characteristics". Until now, only limited options are available in a photolithographic system to sense such beam quality characteristics and to control such characteristics. Specifically, when a radiation beam lacks a proper dimensioning and homogeneity, this effects the ellipticity of the image, causing a different imaging quality in horizontal and vertical directions of a wafer.

As a rule, a photolithographic system comprises a radiation system, such as a laser system, which provides a radiation beam that is further lead into the system towards the patterning means. Such radiation system is a unit which is generally positioned at a certain distance of the unit where the support structure, the projection system and the substrate table are located.

To further guide the beam towards the support structure for supporting patterning means and to control the illumination time thereof, an illumination system is used. Hence, in a conventional system, the beam travels from the radiation system to the illumination system, and, while entering the illumination system simple conditioning of the beam is possible, such as manually adjusting an optical unit in order to modify the diameter of the beam in two different directions; directing the beam by a first steering mirror towards an aperture in the illumination system and then steering the beam by a second steering mirror in order to provide the proper pointing direction of the

mirror through said aperture. Such a setup is illustrated in more detail with reference to figure 2.

In order to identify the beam quality characteristics of the beam while entering the illumination unit, conventionally, a camera is placed in the optical path of the beam and the dimensions of the beams are graphically recorded. This graphical recording is analyzed. Based on such graphical recording the optical unit is manually adjusted. This process is repeated until a proper graphic recording is achieved, so that the beam is tuned once and for all, until a new adjustment of the lithographic system appears necessary. It is clear that this process is tedious and time-consuming, let alone mentioning the costs involved of keeping the apparatus in a non-productive state.

Furthermore, although considered quite relevant for achieving optimal illumination conditions, no procedure exists in order to measure a beam divergence of the beam, which although small, may be able to influence the system in a quite severe manner, since in a photolithographic system the imaging of the pupil will be distorted depending on such quality characteristics. Therefore, the homogeneity of intensity distribution of the radiation beam near the patterning means is influenced, which affects the quality of the photolithographic process.

In known photolithographic apparatuses a so-called Beam Measuring Unit (BMU) is present, and an Energy Sensor (ES). The beam measuring unit BMU is able to control the first and second steering mirror in order to provide a predetermined entering position and pointing of the radiation beam into the system. It comprises focusing elements which images split versions of the beam on positional sensors, the position on the sensors being indicative for the entering position and/or pointing direction of the beam.

The Energy Sensor is capturing a split version of the beam and measuring an energy influx, in order to provide a dose control for a target portion of the substrate.

It is an object of the invention to provide a lithographic projection apparatus, wherein an improved control of quality characteristics of a radiation beam for illumination of a substrate is achieved. It is a further object of the invention to provide a photolithographic system, wherein such quality characteristics can be measured and controlled without drastic modifications of existent photolithographic systems. It is a further object of the invention to use the Energy Sensor (ES) unit and Beam Measuring Unit (BMU) to identify and control such quality characteristics of the radiation beam as beam diameter and beam divergence. It is a further object to reduce the amount of equipment and workload needed to provide such control. It is a still further object of the invention to provide a method for determining a beam diameter of a projection beam of radiation in a photolithographic apparatus, substantially improving the known procedures of adjusting and tuning beam characteristics.

According to the invention, these and other objects are achieved in a lithographic apparatus as specified in the preamble of claim 1, wherein the lithographic apparatus comprises a processing unit coupled to said means for directing the projection beam in order to vary the throughput of said projection beam through said aperture by a relative movement of the projection beam and said aperture, the processing unit further coupled to said detector ES for detecting said throughput, the processor arranged to calculate the beam diameter as a function of detected throughput and relative movement.

The invention provides a simple technique for identifying such characteristics of interest, thus eliminating the need of long interruptions caused by disassembly of the illumination unit and placing separate test equipment which is not functional during the actual lithographic process. By reducing/increasing the throughput through the aperture, the amount of

radiation incident on the detector ES will be reduced/increased. Hence, by determining the relative displacement of the aperture and the radiation beam while measuring the amount of incident radiation, in a simple way, the diameter of the beam can be determined. Hence, an improved and actual online control of the light beam quality characteristics is possible by using the photolithographic system according to the invention.

In a preferred embodiment, the processor is arranged for receiving a first relative throughput at a first relative position of the projection beam and for receiving a second relative throughput at a second relative position of the projection beam; wherein the processor is arranged to calculate the beam diameter as a ratio of differences of first and second relative positions and first and second relative throughputs. Since in middle positions between a complete shut-off of the radiation and a complete pass-through of the radiation a linear relationship exists between the displacement and the measured energy, from this relationship the total diameter can be very easily determined by intrapolation.

In a further embodiment, said means for varying the throughput of the projection beam comprises a first rotatable steering mirror coupled to said processor. In such an arrangement the processor may calculate a relative movement of said reflected projection beam as a function of a received rotation of said steering mirror and as a function of a predetermined beam delivery length between said steering mirror and said aperture. As mentioned before such a steering mirror may already be present in the system, where, by very simple adaptation and measuring of the rotation angle, from a known beam delivery length, the displacement at the position of the aperture may be determined. In this respect, the term "beam delivery length" refers to an optical distance traveled by a radiation beam between, in this case, the steering mirror and the aperture.

In such a steering mirror arrangement, the processor may be arranged for receiving a third relative throughput at a third relative position of the projection beam, wherein the projection beam at least partially overlaps the aperture on a first side of the aperture and for receiving a fourth relative throughput at a fourth relative position of the projection beam wherein the projection beam at least partially overlaps the aperture on a second side of the aperture opposite said first side; wherein the processor is arranged to calculate the beam delivery length as a function of said third and fourth rotations and a predetermined distance between said opposite sides of said aperture.

Conveniently said steering mirror may be rotatable in two different directions, so as to measure the beam diameter in two cross-directions.

In the conventional illumination unit, the beam may be further conditioned by splitting and controlling the direction and/or divergence of the split beams; this is usually performed by a so-called diffracting optical element. Although for applying the method of the invention, any aperture placed in the radiation path of the beam may be used for determining a beam diameter, in a preferred embodiment, the aperture through which the projection beam is directed, is formed by the edges of such a diffracting optical element. Therefore, as a preferred embodiment, the photolithographic system according to the invention is equipped with a conventional steering mirror, a conventional diffracting optical element serving as an aperture and a conventional energy detector which is also already present for detecting the amount of energy that is transferred to the substrate, hence, in this respect, no substantive modification of the illumination system is necessary to perform a beam diameter measurement according to the method and apparatus of the invention. Therefore, as a preferred embodiment, the photolithographic system according to the invention is equipped with a conventional steering mirror, a conventional diffracting optical element serving as an aperture and a

conventional energy detector already present for detecting the amount of energy that is transferred to the substrate.

In a further preferred embodiment, the apparatus according to the invention further comprises an optical element for varying the beam width of said projection beam of radiation, said optical element coupled to said processor, so as to tune said projection beam of radiation to a predetermined beam width. In this way, a direct feedback loop can be formed to control the beam diameter and inaccurate manual tuning and adjustment of the optical element for varying the beam width can be avoided.

In a still further preferred embodiment of the invention, a focusing element having a predetermined focusing power may be arranged to image said projection beam of radiation in a focus plane; said aperture and said detector are then arranged in a focus plane of said focusing element. According to the invention the processor may also be arranged to calculate the beam diameter of said imaged projection beam of radiation; and the processor further arranged to calculate a beam divergence of said projection beam of radiation as a function of said calculated beam diameter of said imaged projection beam of radiation, a predetermined beam diameter of the projection beam and said focusing power of said focusing element. In this embodiment, the out-of-focus amount of the beam can be measured by calculating the beam diameter in the focal position; this out-of-focus amount can be associated to a beam divergence of the input radiation beam. Since such focusing element may already be present, the invention offers, by slight modifications of detection and control systems, an elegant possibility to measure the beam divergence, which was previously undetected. Therefore, in addition to the earlier described setup for measuring a beam diameter, in this further preferred embodiment, also beam divergence measurements are possible by using the fact that a diverging beam produces an out of focus beam image; the amount of

out of focus is reflected in the beam diameter; hence, using said focusing element, such as a focusing lens or mirror, a direct measurement of the divergence is possible.

The detector for measuring said beam diameter may be a positional detector, the lithographic projection apparatus further comprising a second steering mirror for varying a relative direction of said projection beam of radiation; the positional detector indicating said relative direction of the lightbeam. This conventional arrangement is used alternatively to not only identify the position and direction of the beam by using a positional measurement, but also, by determining the beam size of the imaged beam, the divergence of said beam.

In an optical light path of said projection beam of radiation, said first steering mirror may be provided before a second steering mirror, in such a way, that said first steering mirror moves a relative position of said projection beam of radiation and said second steering mirror moves a relative direction of said projection beam of radiation. In this arrangement, both beam diameter and divergence can be measured.

According to a further aspect of the invention there is provided a method of determining a beam diameter of a projection beam of radiation in a photolithographic apparatus, comprising the steps of:

providing a projection beam of radiation;

providing an aperture, through which the projection beam is directed;

providing a detector for detecting a throughput of the projection beam through the aperture;

varying the throughput of the projection beam through said aperture by moving the aperture and the projection beam relatively towards each other;

detecting the throughput relative to a maximum throughput of the projection beam through the aperture as a function of relative movement;

determining the beam diameter from the detected throughput and relative movement; and

varying the beam width of said projection beam of radiation, so as to tune said projection beam of radiation to a predetermined beam width.

In a first embodiment according to the method of the invention, the method may comprise detecting a first relative throughput at a first relative position of the projection beam; detecting a second relative throughput at a second relative position of the projection beam; and calculating the beam diameter as a ratio of differences of first and second relative positions and first and second relative throughputs. Preferably said first and second relative positions correspond to 10% and 90% relative throughput of the projection beam. The method may further comprise providing a first rotatable steering mirror;

fixing said aperture in relation to said steering mirror;

reflecting said projection beam of radiation by said steering mirror;

measuring a relative movement of said reflected projection beam of radiation as a function of rotation of said steering mirror and as a function of a predetermined beam delivery length between said steering mirror and said aperture.

In this arrangement, the method may comprise detecting a third relative throughput at a third relative position of the projection beam corresponding to a third relative rotation of the steering mirror, wherein the projection beam at least partially overlap the aperture on a first side; detecting a fourth relative throughput at a fourth relative position of the projection beam corresponding to a fourth relative rotation of the steering mirror, wherein the projection beam at least partially overlap the aperture on a second side opposite said first side; and calculating the beam delivery length as a function of said third and fourth rotations and a predetermined distance between said opposite sides of said aperture. Said third and fourth relative

positions may correspond to 50% relative throughput of the projection beam. Said beam diameter may be measured in two different directions, more particular, the projection beam may be moved relative to the aperture in two different directions.

In a further preferred embodiment, the method may comprise providing a projection beam of radiation; providing a focusing element; imaging said projection beam of radiation in a focus plane by said focusing element; and measuring the beam diameter of said imaged projection beam of radiation as a measure for determining the beam divergence.

Preferably said measurement is performed by a beam diameter measurement of the above described kind; however the invention is not limited thereto; other measurement methods for measuring the beam diameter of said imaged projection beam may be applied.

In a preferred embodiment, the (absolute) divergence of said projection beam may be calculated as a function of beam diameter of the projection beam, focussing power of said focusing element and measured beam diameter of said imaged projection beam by said focussing element.

In this way, an elegant way for determining the beam divergence is offered. Said imaged projection beam of radiation may be incident on a positional detector arranged in the focus plane of said focusing element, wherein a relative incident position of said imaged projection beam of radiation on said positional detector is indicative for the direction of the lightbeam. The positional detector may comprise a fixed aperture.

Although specific reference may be made in this text to the use of the apparatus according to the invention in the manufacture of ICs, it should be explicitly understood that such an apparatus has many other possible applications. For example, it may be employed in the manufacture of

integrated optical systems, guidance and detection patterns for magnetic domain memories, liquid crystal display panels, thin film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms "reticle", "wafer" or "die" in this text should be considered as being replaced by the more general terms "mask", "substrate" and "target portion", respectively.

In the present document, the terms “radiation” and “beam” are used to encompass all types of electromagnetic radiation, including ultraviolet (UV) radiation (e.g. with a wavelength of 365, 248, 193, 157 or 126 nm) and extreme ultra-violet (EUV) radiation (e.g. having a wavelength in the range 5-20 nm), as well as particle beams, such as ion beams or electron beams.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings in which corresponding reference symbols indicate corresponding parts, and in which:

Figure 1 depicts a lithographic projection apparatus according to an embodiment of the invention;

Figure 2 schematically depicts the LA-Ex-IL elements of fig. 1;

Figure 3 schematically illustrates a diagram of an ES signal in relation to a rotation angle of a steering mirror; corresponding relative positions of the radiation beam and the aperture are depicted below said diagram;

Figure 4 depicts an energy signal measured in two dimensions for relative rotation in an X- and in a Y-direction;

Figure 5 depicts a more detailed illustration of the Beam Measuring Unit illustrated in figure 2;

Figure 6 depicts focussing images for a parallel light beam (a); a diverging light beam (b) and a converging light beam (c);

Figure 7 depicts measurement results in the X-direction;

Figure 8 depicts measurement results in the Y-direction.

Embodiment 1 - measuring beam diameter.

Figure 1 schematically depicts a lithographic projection apparatus 1 according to a particular embodiment of the invention. The apparatus comprises:

- a radiation system Ex, IL, for supplying a projection beam PB of radiation (e.g. light in the deep ultraviolet region). In this particular case, the radiation system also comprises a radiation source LA;
- a first object table (mask table) MT provided with a mask holder for holding a mask MA (e.g. a reticle), and connected to first positioning means PM for accurately positioning the mask with respect to item PL;
- a second object table (substrate table) WT provided with a substrate holder for holding a substrate W (e.g. a resistcoated silicon wafer), and connected to second positioning means PW for accurately positioning the substrate with respect to item PL; and
- a projection system ("lens") PL for imaging an irradiated portion of the mask MA onto a target portion C (e.g. comprising one or more dies) of the substrate W.

As here depicted, the apparatus is of a reflective type (i.e. has a reflective mask). However, in general, it may also be of a transmissive type, for example (with a transmissive mask). Alternatively, the apparatus may employ another kind of patterning means, such as a programmable mirror array of a type as referred to above.

The source LA (e.g. an excimer laser source) produces a beam of radiation. This beam is fed into an ILlumination system (illuminator) IL, either directly or after having traversed conditioning means, such as a beam expander Ex, for example. The illuminator IL may comprise adjusting means AM for setting the outer and/or inner radial extent (commonly referred to as s-outer and s-inner, respectively) of the intensity distribution in the beam. In

addition, it will generally comprise various other components, such as an integrator IN and a condenser CO. In this way, the beam PB impinging on the mask MA has a desired uniformity and intensity distribution in its cross-section.

It should be noted with regard to figure 1 that the source LA may be within the housing of the lithographic projection apparatus (as is often the case when the source LA is a mercury lamp, for example), but that it may also be remote from the lithographic projection apparatus, the radiation beam which it produces being led into the apparatus (e.g. with the aid of suitable directing mirrors 2); this latter scenario is often the case when the source LA is an excimer laser. The current invention and claims encompass both of these scenarios.

The beam PB subsequently intercepts the mask MA, which is held on a mask table MT. Having traversed the mask MA, the beam PB passes through the lens PL, which focuses the beam PB onto a target portion C of the substrate W. With the aid of the second positioning means PW (and interferometric measuring means IF), the substrate table WT can be moved accurately, e.g. so as to position different target portions C in the path of the beam PB. Similarly, the first positioning means PM can be used to accurately position the mask MA with respect to the path of the beam PB, e.g. after mechanical retrieval of the mask MA from a mask library, or during a scan. In general, movement of the object tables MT, WT will be realized with the aid of a long-stroke module (coarse positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in figure 1. However, in the case of a wafer stepper (as opposed to a step-and-scan apparatus) the mask table MT may just be connected to a short stroke actuator, or may be fixed. Mask MA and substrate W may be aligned using mask alignment marks M1, M2 and substrate alignment marks P1, P2.

The depicted apparatus can be used in two different modes:

1. In step mode, the mask table MT is kept essentially stationary, and an entire mask image is projected in one go (i.e. a single "flash") onto a target portion C. The substrate table WT is then shifted in the x and/or y directions so that a different target portion C can be irradiated by the beam PB; and

2. In scan mode, essentially the same scenario applies, except that a given target portion C is not exposed in a single "flash". Instead, the mask table MT is movable in a given direction (the so-called "scan direction", e.g. the y direction) with a speed v, so that the projection beam PB is caused to scan over a mask image; concurrently, the substrate table WT is simultaneously moved in the same or opposite direction at a speed V = Mv, in which M is the magnification of the lens PL (typically, M = 1/4 or 1/5). In this manner, a relatively large target portion C can be exposed, without having to compromise on resolution.

In the photolithographic apparatus 1 a projection beam 3 of radiation is guided through an aperture 4 which is present in the ILlumination system IL; directing mirrors 2 for directing the projection beam 3 through said aperture 4 are present and an energy detector ES for detecting a throughput of the projection beam through said aperture. For determining the beam diameter, in the prior art systems a raster target is used, that is specifically for this purpose placed in the ILlumination unit IL. This target is an expensive tool, the procedure is time-consuming and obviously there is a high risk of contamination of the system. Furthermore, the image acquired by the raster target is not easily readable.

In figure 2, a more detailed illustration is shown of the LA-Ex-IL elements of figure 1. In the figure, the LA-unit is a deep ultraviolet (DUV) excimer laser, although the invention is also applicable for other type of illumination systems. Further, the light beam emanating from the laser is conditioned by the EX unit, which is a unit for adjusting the beam diameter in X- and Y- direction. Conventionally, this unit comprises a manually adjustable

lens system that is movable along an optical axis, the position of the lenses determining the diameter in X- and/or Y-direction. In the beam Expander unit Ex a rotatable steering mirror 21 is present, a rotation of which causes, depending on the axis of rotation, a lateral displacement in X- or Y-direction of the beam near the aperture 4. In this way, the beam 3 can be directed through the aperture 4, which, in this embodiment, is a diffracting optical element (DOE) in an automated DOE-exchange unit. From such an exchange unit, a DOE 4 is selected for further conditioning the beam in a desired way. The modification generally comprises splitting and controlling the direction of the split beams.

In the ILlumination unit IL a fraction of the light beam is guided into the Beam Measuring Unit, which is present for measuring the position and pointing direction of the light beam and will further be explained with reference to figure 5. The majority of the beam travels through the DOE 4 and is guided into the Zoom Axicon AM, which is there for setting the outer and/or inner radial extent (commonly referred to as s-outer and s-inner, respectively) of the intensity distribution in the beam. A fraction of the energy of the light beam is guided into Energy Sensor ES, the rest is directed to further elements of the ILlumination unit, such as the integrator IN and condensor CO.

In the Energy Sensor, the amount of energy is calculated that is impingent on the wafer in the wafer stage, which amount is relevant for the photosensitive materials applied in photolithography. In this embodiment, the diameter of beam 3 is measured by a processing unit 5 coupled to the steering mirror 21, the processor measuring a rotation angle in relation to a measured energy signal from energy detector ES.

Referring to figure 3, a relation is shown between a rotation angle of steering mirror 21 and the energy signal that is measured in ES. In order to vary the throughput of said projection beam through said aperture by a relative movement of the projection beam and said aperture, the processing is

coupled to the steering mirror 21 and is further coupled to said detector ES for detecting said throughput. The processor is arranged to calculate the beam diameter from the obtained energy values as a function of angular displacement.

The figure 3 can be understood as follows: starting from a rotation directing the beam to the far left side of the positionally fixed DOE 4, the beam is blocked by edge 6 of the DOE 4. Then, by rotating the steering mirror 21 clockwise, the beam throughput through DOE 4 is increased according to the functional relationship depicted in the upper diagram of the figure. By continuing the rotation, eventually, the beam 3 is blocked partially and eventually completely by the opposite edge 7 of DOE.

The steps for determining the beam diameter 31 are now as follows: in a first step, delivery length is determined from the 50% points of the energy diagram, which is equivalent to a rotational distance α indicated in fig. 3:

$$\textit{length beam delivery}\,[m] = \frac{\textit{size aperture}[mm]}{\alpha\,[mm/m]} \qquad [1]$$

Then, the difference in angle between two positions of the mirror 21 is measured, wherein in a first position the measured throughput is relatively small, for example 10%, and in a second position the measured throughput is relatively large, for example 90% of the maximum. These two angular positions are used to calculate the beam size. This done with the following formula:

$$\textit{beam size}\,[mm] = \beta\,[mm/m] * \textit{length beam delivery}\,[m] \qquad [2]$$

or with [1]:

$$beam\ size\,[mm] = \frac{\beta\,[mm/m]}{\alpha\,[mm/m]} * size\ aperture\,[mm] \qquad [3]$$

In this procedure, only 80% of the diameter (i.e. the 10-90% points) is actually measured hence the "actual" beam size is then a factor 1.25 larger, assuming a linear relationship between energy intensity and angular displacement. The processor is arranged to calculate the beam diameter as a ratio of differences of first and second relative positions and first and second relative throughputs.

In fig. 4, a two-dimensional plot is shown of actual measurement results in a photolithographic system, wherein for a matrix of 25 x 25 positions the energy throughput was measured. From the figure it is apparent that the laser beam is quite sharply defined in the X-direction since the 10% and 90% positions are quite close, in the Y-direction the beam is smeared over a larger distance. From this two-dimensional plot, a diameter of the beam can be calculated along a cross-section, where the 10, 50 and 90% points are calculated by linear interpolation and are translated in a mirror angle.

The results are illustrated in the following table:

parameter	'left' axis 2 position [steps]	'left' axis 2 angle [mrad]	'right' axis 2 position [steps]	'right' axis 2 angle [mrad]
10%	-2149	-3.83	6191	5.44
50%	-571	-1.02	4577	7.99
90%	807	1.45	3068	10.55
α		9.01mrad		9.01mrad
β		5.28mrad		5.11mrad
DOE size		50mm		50mm
1.25 x beam x-size		36.6mm		35.5 mm

Table 1

Next, a check was performed by measuring the beam diameter via a conventional camera tool placed in the BMU and a frame grabber looking on the raster target. The result (37 mm) matched perfectly with the calculated values from table 1.

Embodiment 2 –measuring beam divergence.

In fig. 5, a detailed illustration is given of beam measuring unit BMU 8. From the DUV laser beam 3 that propagates in the direction of the zoom-axicon AM 1% is split off by the incoupling mirror 9. The split beam 10 travels

through lens 11 and via a reflective mirror 12 to a second semi-reflective mirror 13, which splits the DUV laser beam 10 in two halves. The part that passes mirror 13 is imaged by lens 14 on a fluorescent (in this example: YAG:Ce) target 15. The other part of the beam that is reflected by mirror 13 is focussed by lens 16 on the second fluorescent target 17. The construction of both optical paths is such that the combination of lens 11 and 14 makes an image of the DUV laser beam on the fluorescent YAG:Ce target 15, while the combination of lens 11 and 16 focuses the DUV laser beam 10 on the fluorescent target 17. Consequently the lens 11 and 14 combination is used for measuring the position of the beam, while the lens 11 and 16 combination is used for measuring the pointing of the laser beam. The deep ultraviolet light is absorbed in the YAG:Ce crystal. This crystal emits visible light that is imaged 1:1 on Position Sensitive Devices 18, 19(PSD) with lenses 20.

The beam will be focussed on the pointing PSD 18 (see Fig. 6(a)) in case of a parallel beam and if lenses 11 and 16 are well aligned/positioned. If the beam is converging or diverging a defocussed image is received on the pointing PSD 18 (see respectively Fig 6 (b) and (c)). For the divergence measurement the sum signal of the pointing PSD 18 must be measured.

The diameter of the defocussed image is a measure for the divergence or convergence of the beam and can be measured by scanning the (de)focussed image with the BM beam steering mirror 22 over the diaphragm 21 in front of the PSD unit 18, as explained with reference to embodiment 1.

Next, the results of divergence measurements are illustrated in figs. 7 and 8 for perpendicular cross-sections of the laser beam. The results of figure 7 are listed in table 2:

parameter	'left' axis 3 position [steps]	'left' axis 3 angle [mrad]	'right' axis 3 position [steps]	'right' axis 3 angle [mrad]
10%	-1703	-3.04	3140	3.59
50%	-1070	-1.91	2580	4.59
90%	-508	-0.91	2009	5.56
α		6.50mrad		6.50mrad
β		2.13mrad		1.97mrad

Table 2

Angle β i.e. the difference in angle between the two positions of the BM BXP mirror 22 where 10% and 90% of the maximum sum signal of the pointing PSD 18 is a measure for the beam divergence in the x and y direction.

Angle β can be directly calculated/derived from the BM beam steering mirror 22 position [steps].

$$\textit{beam divergence}\,[mrad] \equiv \beta\,[mrad] = \left|angle_{10\%} - angle_{90\%}\right| \qquad [4]$$

The following table illustrates the results of the divergence measurement according to the invention compared to a divergence measurement through conventional measurement with a photographical recording on a predetermined number of positions in the radiation path of the

projection beam. It is noted that beam divergence measured according to the method of the invention is in accordance with the beam divergence measured from conventional divergence measurements.

Parameter	beam divergence according to the invention [mrad]	conventional beam divergence measurement [mrad]
divergence x	2.15/0.8 = 2.69	2.87±0.2
divergence y	0.21/0.8 = 0.26	0.14±0.2

Table 3

In the method of the invention, it is not immediately recognized whether the beam is diverging (+ sign) or converging (- sign). This ambiguity can be solved by performing a measurement twice with a projection beam that is slightly different in diameter.

It is noted that while in the described embodiments, a single scan in one dimension is performed for measuring a beam diameter; actually, a beam diameter may be scanned multiple times for obtaining an accurate 2 D impression of the beam cross-section. It is noted that where applicable in the text, when the term optical or focusing element is used such may be a composite element or a set of separate objects providing the effect. Whilst specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The description is not intended to limit the invention.

Claims

1. A lithographic projection apparatus comprising:

– a radiation system for providing a projection beam of radiation;

– a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;

– a substrate table for holding a substrate;

– a projection system for projecting the patterned beam onto a target portion of the substrate;

– an aperture, through which the projection beam is directed;

– a detector ES for detecting a throughput of the projection beam through said aperture;

– means for directing the projection beam through said aperture;

characterized in that the lithographic projection apparatus comprises

– a processing unit coupled to said means for directing the projection beam in order to vary the throughput of said projection beam through said aperture by a relative movement of the projection beam and said aperture, the processing unit further coupled to said detector ES for detecting said throughput, the processor arranged to calculate the beam diameter as a function of detected throughput and relative movement.

2. A lithographic projection apparatus according to claim 1, wherein the processor is arranged for receiving a relatively small first throughput at a first relative position of the projection beam and for receiving a relatively large second throughput at a second relative position of the projection beam; wherein the processor is arranged to calculate the beam diameter as a distance between said first and second relative positions.

3. A lithographic projection apparatus according to any of claims 1 -2, wherein the processor is arranged for receiving a first relative throughput at a first relative position of the projection beam and for receiving a second relative throughput at a second relative position of the projection beam; wherein the processor is arranged to calculate the beam diameter as a ratio of differences of first and second relative positions and first and second relative throughputs.

4. A lithographic projection apparatus according to any of claims 1-3, wherein said means for varying the throughput of the projection beam comprise a first rotatable steering mirror coupled to said processor; and wherein said processor is arranged to calculate a relative movement of said reflected projection beam as a function of a received rotation of said steering mirror and as a function of a predetermined beam delivery length between said steering mirror and said aperture.

5. A lithographic projection apparatus according to claim 4, wherein the processor is arranged for receiving a third relative throughput at a third relative position of the projection beam, wherein the projection beam at least partially overlaps the aperture on a first side of the aperture and for receiving a fourth relative throughput at a fourth relative position of the projection beam wherein the projection beam at least partially overlaps the aperture on a second side of the aperture opposite said first side; wherein the processor is arranged to calculate the beam delivery length as a function of said third and fourth rotations and a predetermined distance between said opposite sides of said aperture.

6. A lithographic projection apparatus according to any of claims 1-5 , wherein said steering mirror is rotatable in two different directions.

7. A lithographic projection apparatus according to any of claims 1-6, characterized in that said aperture is formed by the edges of a diffracting optical element.

8. A lithographic projection apparatus according to any of claims 1-7, further comprising an optical element for varying the beam width of said projection beam of radiation, said optical element coupled to said processor, so as to tune said projection beam of radiation to a predetermined beam width.

9. A lithographic projection apparatus according to any of claims 1-8, further comprising:

– a focusing element arranged to image said projection beam of radiation in a focus plane; wherein said aperture and said detector are arranged in a focus plane of said focusing element and wherein the processor is arranged to calculate the beam diameter of said imaged projection beam of radiation as a measure of a beam divergence of said projection beam of radiation.

10. A lithographic projection apparatus according to claim 9, wherein said detector is a positional detector, the lithographic projection apparatus further comprising a second steering mirror for varying a relative direction of said projection beam of radiation; the positional detector indicating said relative direction of the lightbeam.

11. A lithographic projection apparatus according to claim 10, wherein, in an optical light path of said projection beam of radiation, said first steering mirror is provided before a second steering mirror, in such a way, that said first steering mirror moves a relative position of said projection beam of radiation and said second steering mirror moves a relative direction of said projection beam of radiation.

12. Method of determining a beam diameter of a projection beam of radiation in a photolithographic apparatus, the method comprising the steps of:

– providing a projection beam of radiation;
– providing an aperture;
– providing a detector for detecting a throughput of the projection beam through the aperture;
– varying the throughput of the projection beam through said aperture by moving the aperture and the projection beam relatively towards each other;
– detecting the throughput relative to a maximum throughput of the projection beam through the aperture as a function of relative movement; and
– determining the beam diameter from the detected throughput and relative movement; and
– varying the beam width of said projection beam of radiation, so as to tune said projection beam of radiation to a predetermined beam width.

13. Method according to claim 12, characterized in that the method comprises the steps of

– detecting a relatively small first throughput at a first relative position of the projection beam;
– detecting a relatively large second throughput at a second relative position of the projection beam; and
– calculating the beam diameter as a distance between said first and second relative positions.

14. Method according to claim 12 or 13, characterized in that the method comprises the steps of:

– detecting a first relative throughput at a first relative position of the projection beam;

– detecting a second relative throughput at a second relative position of the projection beam; and

– calculating the beam diameter as a ratio of differences of first and second relative positions and first and second relative throughputs.

15. Method according to claim 13, wherein said first and second relative positions correspond to 10% and 90% relative throughput of the projection beam.

16. Method according to any of the preceding claims, further comprising the steps of:

– providing a first rotatable steering mirror;

– fixing said aperture in relation to said steering mirror;

– reflecting said projection beam of radiation by said steering mirror;

– measuring a relative movement of said reflected projection beam of radiation as a function of rotation of said steering mirror and as a function of a predetermined beam delivery length between said steering mirror and said aperture.

17. Method according to claim 16, further comprising the steps of:

– detecting a third relative throughput at a third relative position of the projection beam corresponding to a third relative rotation of the steering mirror, wherein the projection beam at least partially overlap the aperture on a first side;

– detecting a fourth relative throughput at a fourth relative position of the projection beam corresponding to a fourth relative rotation of the steering mirror, wherein the projection beam at least partially overlap the aperture on a second side opposite said first side;

– calculating the beam delivery length as a function of said third and fourth rotations and a predetermined distance between said opposite sides of said aperture.

18. Method according to claim 17, wherein said third and fourth relative positions correspond to 50% relative throughput of the projection beam.

19. Method according to any of the preceding claims, wherein said beam diameter is measured in two different directions.

20. Method according to claim 19, wherein the projection beam is moved relative to the aperture in two different directions.

21. Method of determining a beam divergence of a projection beam of radiation in a photolithographic apparatus, the method comprising the steps of:

– providing a projection beam of radiation;
– providing a focusing element;
– imaging said projection beam of radiation in a focus plane by said focusing element; and
– measuring the beam diameter of said imaged projection beam of radiation by a method according any of the preceding claims as a measure for determining the beam divergence.

22. Method according to claim 21, wherein the divergence of said projection beam is calculated as a function of beam diameter of the projection beam, a focussing power of said focusing element and measured beam diameter of said imaged projection beam by said focussing element.

23. Method according to claim 21 or 22, wherein said imaged projection beam of radiation is incident on a positional detector arranged in the focus

plane of said focusing element, wherein a relative incident position of said imaged projection beam of radiation on said positional detector is indicative for the direction of the lightbeam.

24. Method according to claim 23, wherein said positional detector comprises a fixed aperture.

25. Method according to any of claims 21-24, wherein the beam delivery length is measured by rotating a first steering mirror; and wherein the beam divergence of said imaged projection beam of radiation is determined by rotating a second steering mirror.

26. Method according to claim 25, wherein, in an optical light path of said projection beam of radiation, said first steering mirror is provided before said second steering mirror, in such a way, that said first steering mirror moves a relative position of said projection beam of radiation and said second steering mirror varies a relative direction of said projection beam of radiation.

27. Method according to claim 22, wherein said predetermined beam diameter is measured by a method of any of claims 12-26.

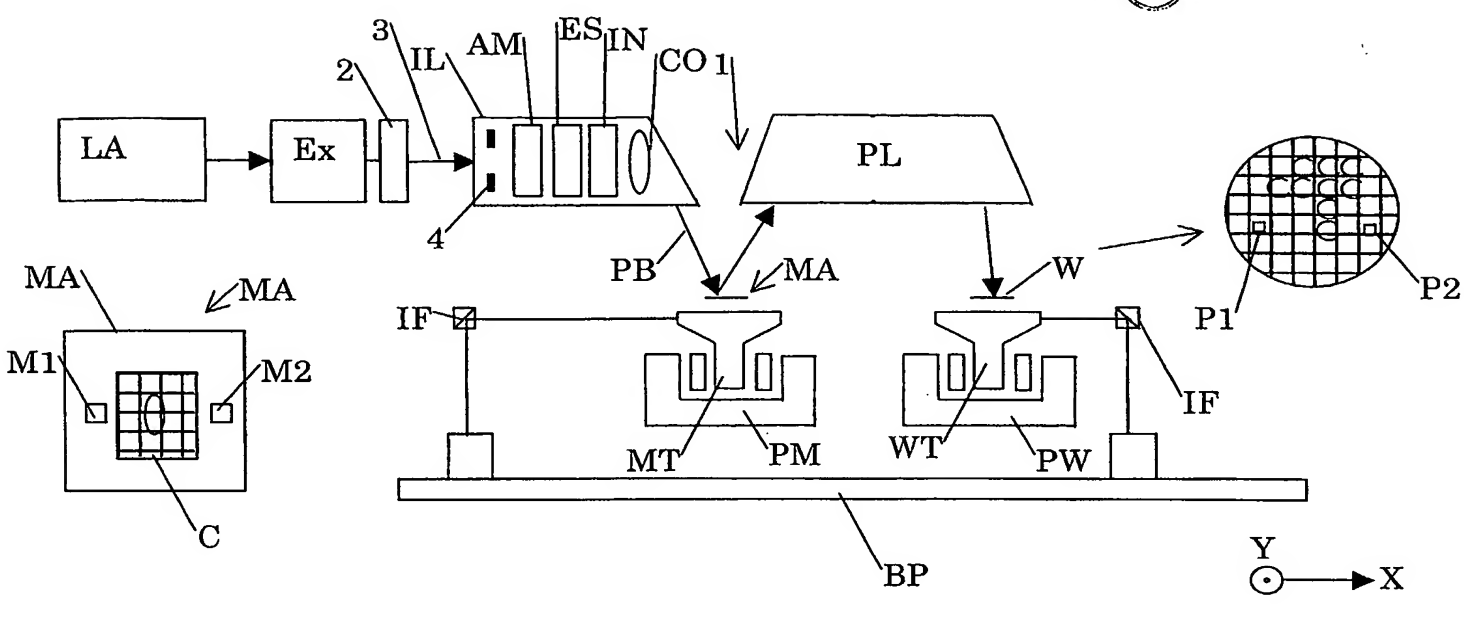
28. Method of determining a beam divergence of a projection beam of radiation in a photolithographic apparatus, the method comprising the steps of:

- providing a projection beam of radiation;
- providing a focusing element;
- imaging said projection beam of radiation in a focus plane by said focusing element; and
- measuring the beam diameter of said imaged projection beam in said focus plane of radiation by a method as a measure for determining the beam divergence.

Abstract

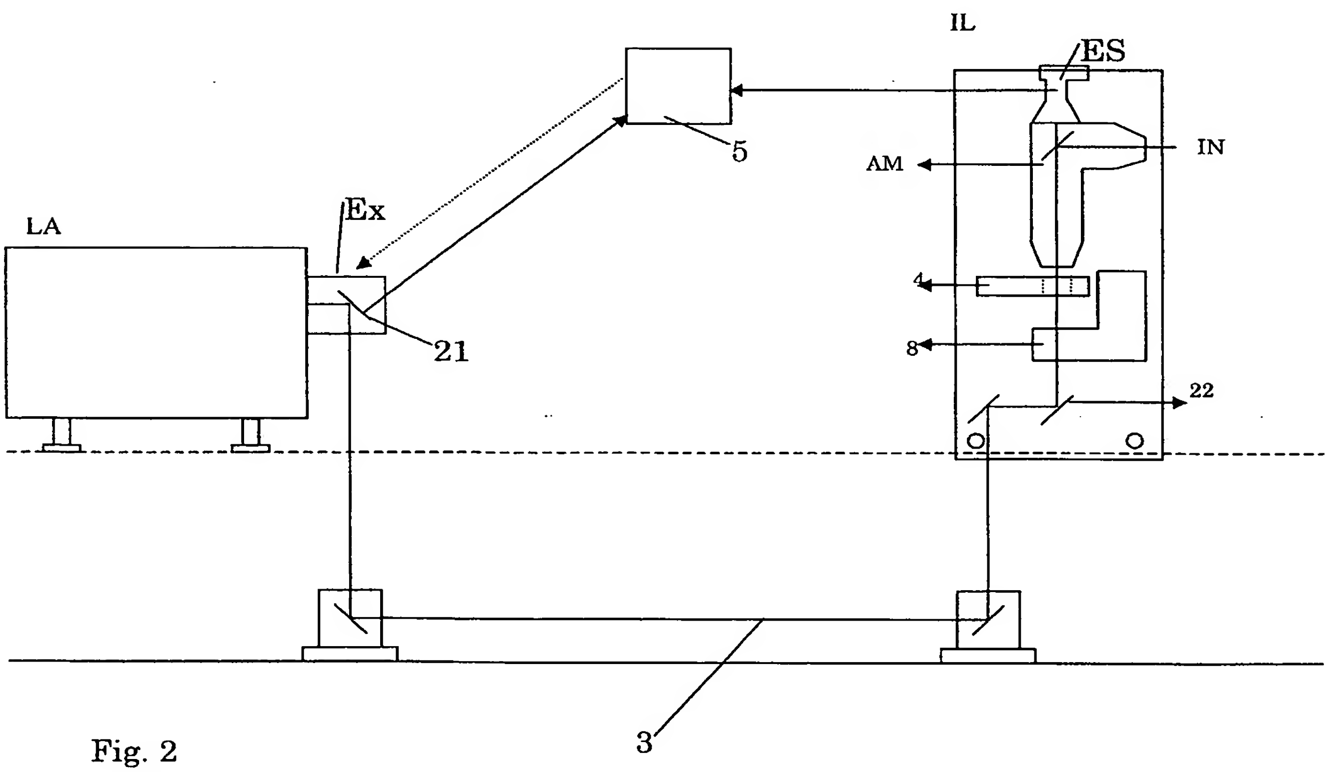
Lithographic Apparatus, Device Manufacturing Method, and Device Manufactured Thereby.

A lithographic projection apparatus comprising a radiation system for providing a projection beam of radiation; an aperture, through which the projection beam is directed; a detector ES for detecting a throughput of the projection beam through said aperture; means for directing the projection beam through said aperture. The lithographic projection apparatus according to the invention comprises a processing unit coupled to said means for directing the projection beam in order to vary the throughput of said projection beam through said aperture by a relative movement of the projection beam and said aperture, the processing unit further coupled to said detector ES for detecting said throughput, the processor arranged to calculate the beam diameter as a function of detected throughput and relative movement. The apparatus of the invention offers a simple and reliable possibility for determining beam quality characteristics such as beam diameter and/or beam divergence.



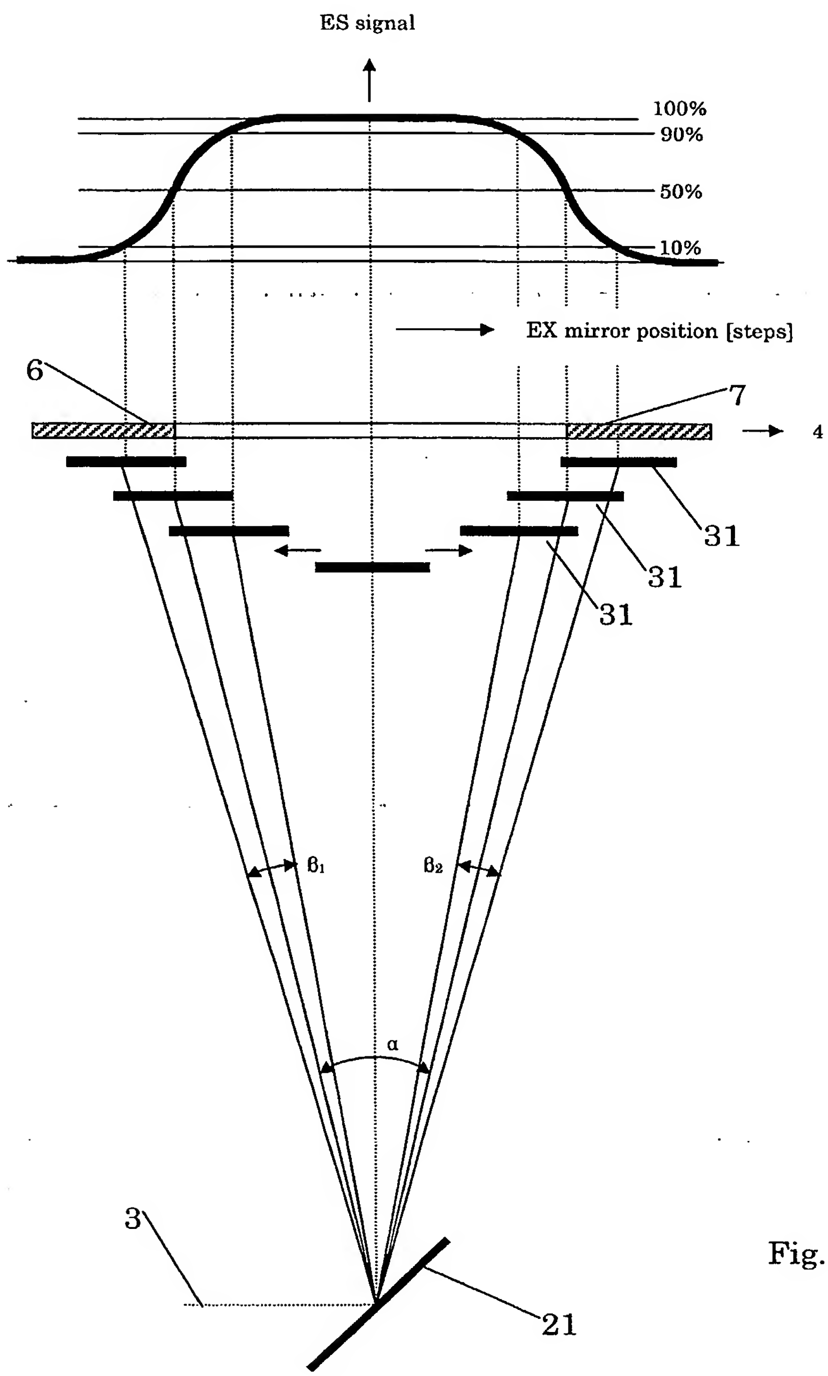
LA
Ex
2
3
IL
AM
ES
IN
CO
1
4
PL
PB
MA
W
P1
P2
IF
MT
PM
WT
PW
BP
M1
M2
C
Y
X

Fig. 1



IL
ES
5
IN
AM
LA
Ex
21
4
8
22
3

Fig. 2



ES signal
100%
90%
50%
10%
EX mirror position [steps]
6
7
4
31
31
31
β1
β2
α
3
21

Fig. 3

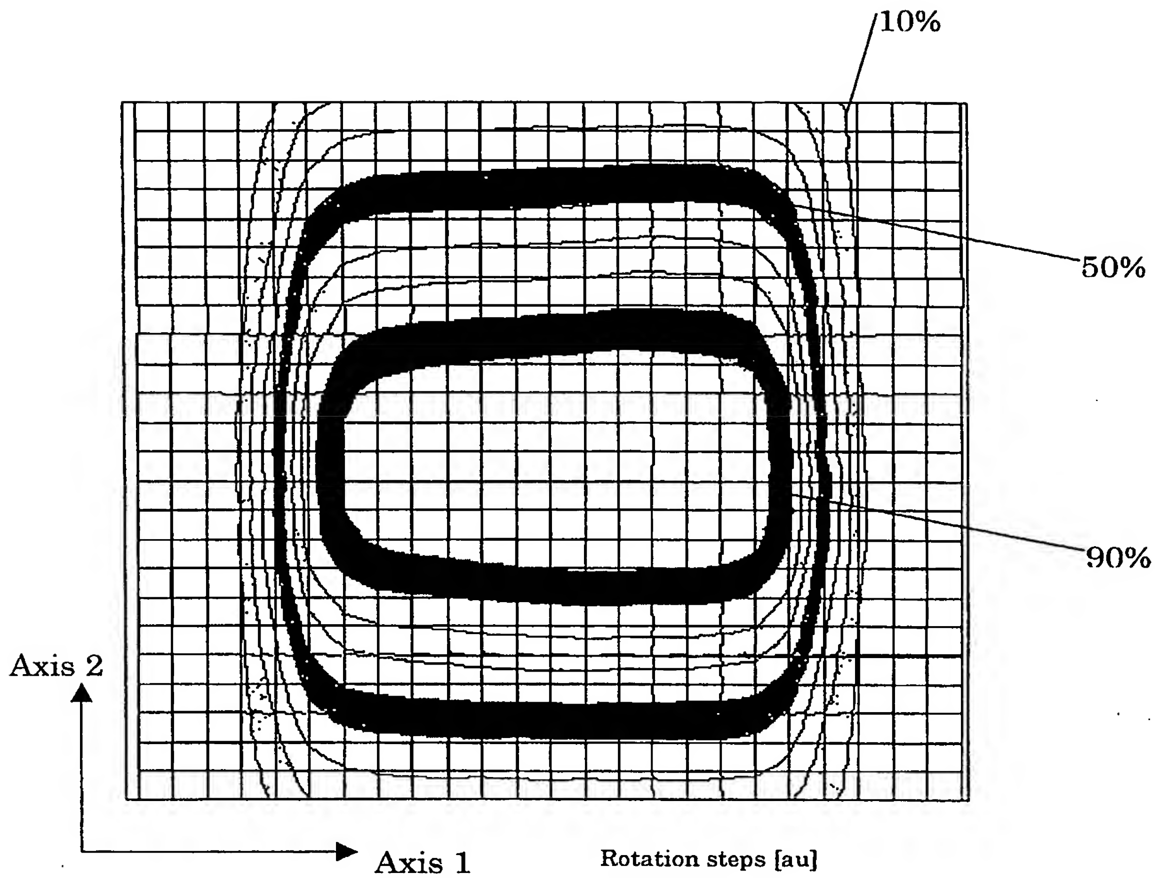


Fig. 4

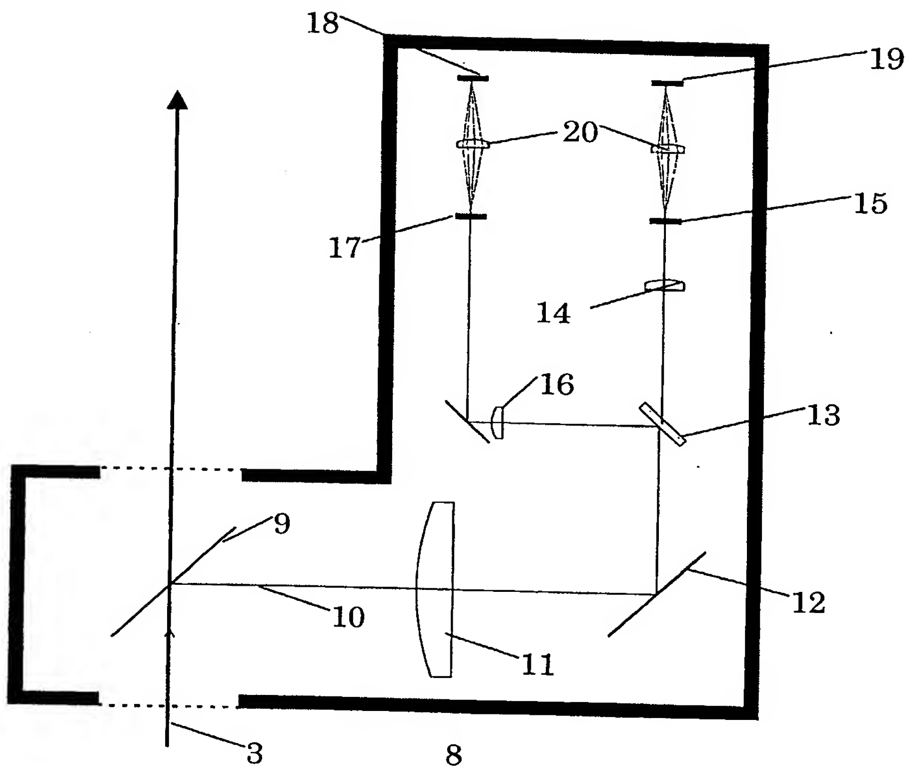

18
19
20
15
17
14
16
13
9
10
12
11
3
8

Fig. 5

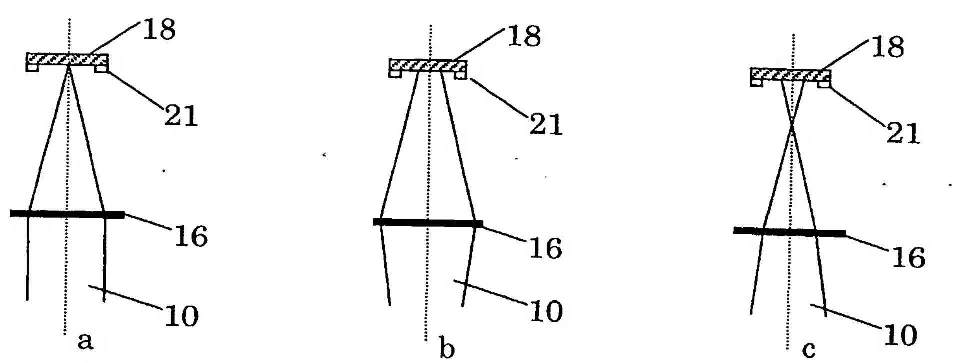

18
21
16
10
a
18
21
16
10
b
18
21
16
10
c

Fig. 6

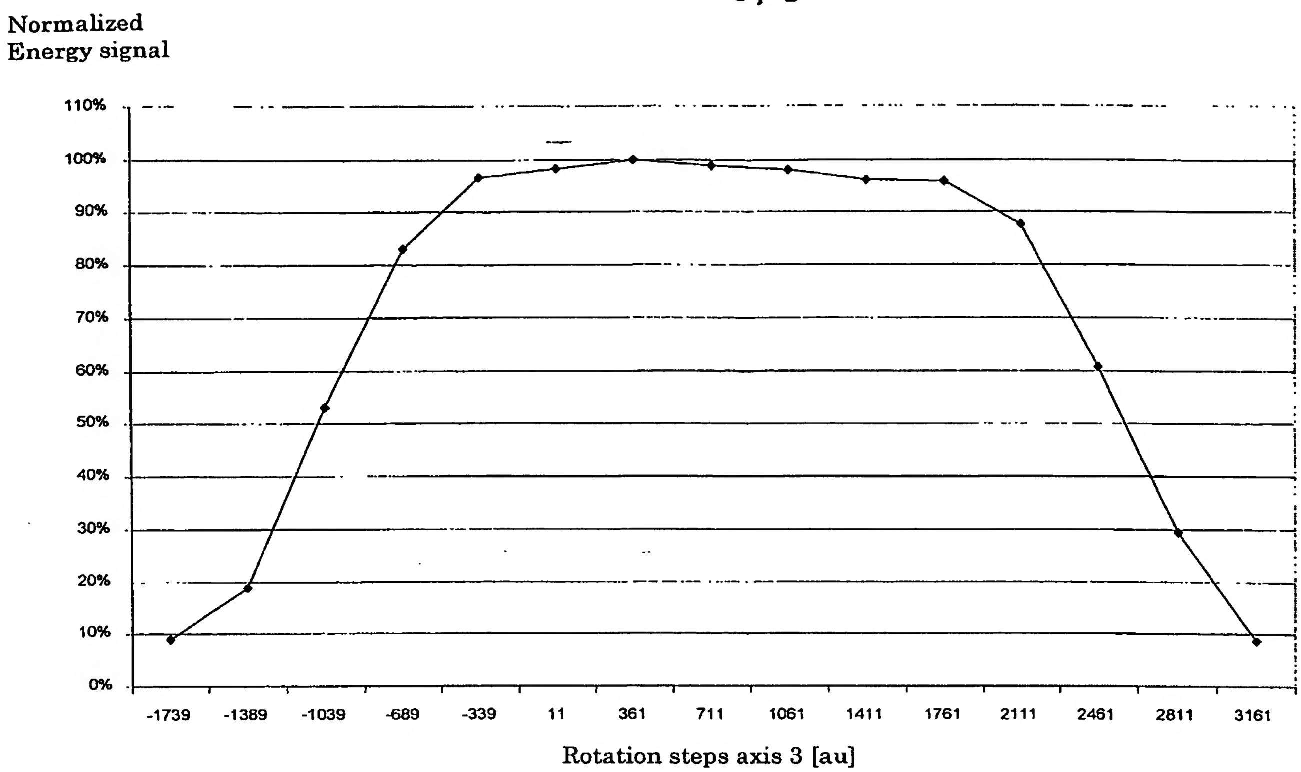

Normalized
Energy signal
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-1739
-1389
-1039
-689
-339
11
361
711
1061
1411
1761
2111
2461
2811
3161
Rotation steps axis 3 [au]

Fig. 7

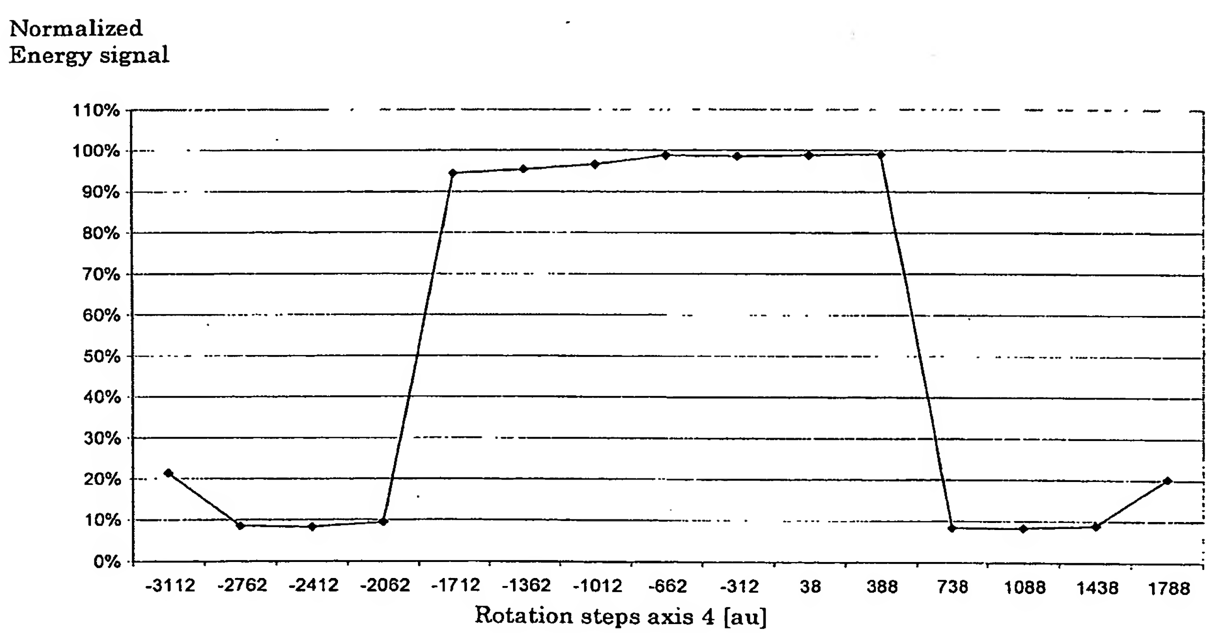

Normalized
Energy signal
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-3112
-2762
-2412
-2062
-1712
-1362
-1012
-662
-312
38
388
738
1088
1438
1788
Rotation steps axis 4 [au]

Fig. 8